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Evidence of deep-blue photon emission at high efficiency by common plastic

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Abstract – Various scintillation devices are used in many countries and wide scientific fields. Key elements that determine the performance of a scintillation device are the number of photons emitted per incident radiation event and the emission of easy-to-measure blue photons. It is generally known that only materials with very complex compositions perform well as scintillators. However, we demonstrated that the scintillation performance of a newly developed plastic such as 100 percent pure polyethylene naphthalate exceeds that of conventional organic scintillators. By measuring the light output spectra and emission spectra of several samples, we revealed that the plastic emits a high number of photons per incident radiation event ($\sim$ 10500 photons/MeV), and, surprisingly, deep-blue photons (425 nm). Even though the plastic has a simple composition, it could replace the expensive organic scintillators that have been used in many applications.

Introduction. – Organic scintillators were developed about 60 years ago to detect radiation [1,2]. To obtain a high scintillation performance, which is evaluated by the number of photons emitted per incident radiation event and by the emission of easy-to-measure deep-blue photons, organic scintillators are manufactured by mixing plastic with chemical additives such as wave shifters [3–12]. However, because the manufacturers keep the detailed information regarding the types and quantities of the wave shifters confidential, organic scintillators are extremely expensive [11].

Recently, we demonstrated that simple plastics such as a plastic bottle could be used as an organic scintillator [13]. However, the plastic bottle emits fewer photons than a conventional organic scintillator; moreover, the ultraviolet photons emitted are difficult to measure.

This prompted us to develop different types of plastics without wave shifters to determine one that performed well as an organic scintillator with wave shifters. After developing many types of plastics, we succeeded in manufacturing a simple plastic such as 100 percent pure polyethylene naphthalate (PEN) is a high scintillation performance.

In this paper, we show that although PEN has a simple composition, it exceeds the performance of conventional scintillators; it emits more photons, and moreover, it emits deep-blue photons.

Materials and methods. – PEN is a thermoplastic polyester synthesized by the polycondensation of dimethyl-2, 6-naphthalenedicarboxylate and ethylene glycol. Unlike specialized organic scintillators, PEN is readily available worldwide because of its common use in everyday objects such as dinner sets (fig. 1). Here, we designed 100 percent pure PEN resin to meet conventional injection molding process. It can make non-crystallized injection molded plate easily. Here, to evaluate PEN's performance as an organic scintillator, a 35 mm × 35 mm × 5 mm PEN plate was manufactured as a homopolymer $[(C_{14}H_{10}O_4)_n]$ by Teijin Chemicals. For comparison, we also obtained same-size samples of a commercial organic scintillator (BC-408; Saint-Gobain Ceramics & Plastic Inc.) and a plastic bottle made from polyethylene terephthalate (Teijin Chemicals Ltd.).

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Table 1: Properties of the three samples used in the present study.

Material	Polyethylene naphthalate	Organic scintillator (ref. [14])	Plastic bottle (ref. [13])
Supplier	Teijin Chemicals	Saint-Gobain	Teijin Chemicals
Base	$(C_{14}H_{10}O_4)_n$	$(C_9H_{10})_n$	$(C_{10}H_8O_4)_n$
Density	$1.33\,g/cm^3$	$1.03\,g/cm^3$	$1.33\,g/cm^3$
Refractive index	1.65	1.58	1.64
Light output	~ 10500 photon/MeV	10000 photon/MeV	~ 2200 photon/MeV
Wavelength max. emission	425 nm	425 nm	380 nm

Fig. 1: Photograph of a dinner set composed of polyethylene naphthalate.

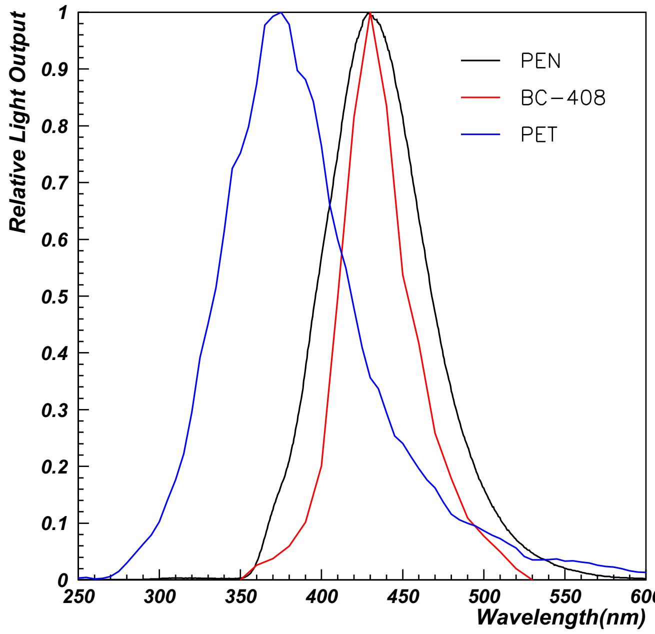

Fig. 3: Emission spectra of polyethylene naphthalate (PEN; black line), commercial organic scintillator (BC-408; red line) and a plastic bottle (PET; blue line).

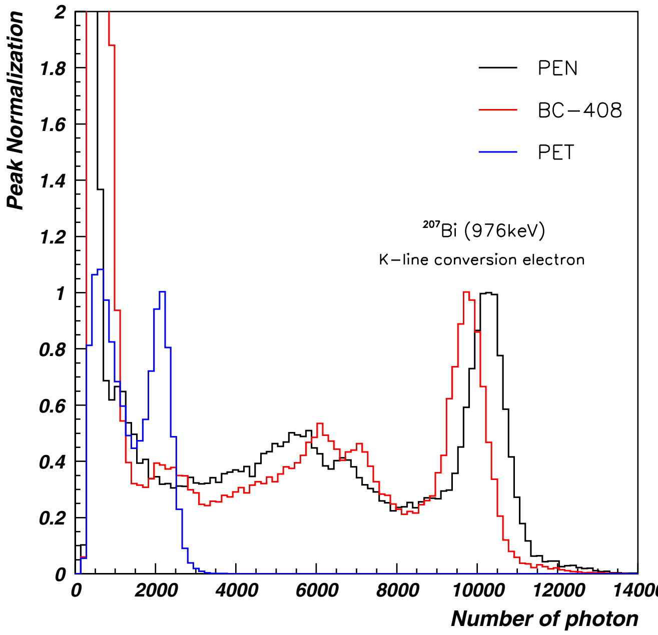

Fig. 2: Light output spectra of polyethylene naphthalate (PEN; black line), commercial organic scintillator (BC-408 (ref. [14]); red line) and a plastic bottle (PET; blue line).

In the experimental setup, one of the $35\,mm^2$ faces of the sample was optically connected to a photomultiplier tube (H7195; Hamamatsu Photonics K.K.) by using optical grease (BC-630; Saint-Gobain Ceramics & Plastic Inc.). A ^{207}Bi radiation source was placed on the $35\,mm^2$ face of each sample, and the light output spectrum of each sample was measured by the 976 keV K-line conversion electrons. Moreover, the emission spectrum of each sample was measured by a spectrometer (F-2700; Hitachi High-Technologies Corp.).

Results and discussions. – The light output spectra of all three samples are presented in fig. 2. As shown by the location of its peak in fig. 2, PEN emits a high number of photons per incident radiation event (~ 10500 photons/MeV): it emits 1.05 and 4.70 times more photons than the organic scintillator and the plastic bottle, respectively. Further, as shown by the full width at half-maximum of its peak in fig. 2, PEN has an energy resolution of $\sim 10\%$ in the 1 MeV region, which is better than that of the commercial organic scintillator. The emission spectra of all three samples are shown in fig. 3. Note that although PEN has a simple composition without wave shifters, it emits deep-blue photons around 425 nm. PEN's emission peak is similar to that of commercial organic scintillators and different from that of PET.

The properties of all three samples are presented in table 1, which indicates that PEN has several excellent features. Note that the primary constituents of PEN are not only hydrogen and carbon but also oxygen. As a result, PEN's density is higher than that of commercial organic scintillators. Further, it is assumed that PEN's long-term reliability might be better than that of commercial organic scintillators because PEN does not contain mixed chemical additives.

Conclusions. – We demonstrated that common plastic PEN sufficiently satisfies the desired performance for scintillation devices [15–17]. PEN is easy to manufacture and handle; moreover, its price is much lower than that of commercial organic scintillators. Because PEN has a high refractive index, it can be used not only in scintillation devices but also in optical devices such as optical fibers. This development opens up opportunity to improve drastically scintillation devices by replacing expensive commercial organic scintillators with cheap common plastics.

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